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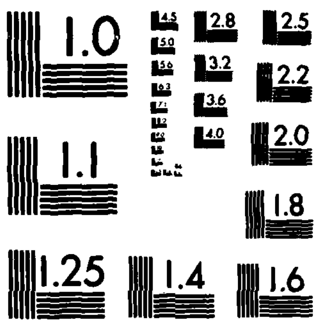

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1. REPORT NUMBER 37	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Techniques for Operating Charge Coupled Devices (CCD's) in Very High Speed Framing Mode		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard S. Aikens, Patrick M. Epperson and M. Bonner Denton		8. CONTRACT OR GRANT NUMBER(s) N00014-83-K-0268
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Chemistry, University of Arizona, Tucson, AZ 85721		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N 051-549
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Arlington, VA 22217		12. REPORT DATE March 19, 1985
		13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Prepared for publication in SPIE Vol. 501: State-of-the-Art Imaging Arrays and Their Application

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Charge Coupled Device (CCD)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Appropriate masking techniques allow a large portion of the CCD to be employed as a high speed image buffer. Applications include spatial imaging of rapidly moving objects, observations of transient spectral chemical phenomena and the —

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Contract N00014-83-K-0268

Task No. NR 051-549

TECHNICAL REPORT NO. 37

Techniques for Operating Charge Coupled Devices (CCD's) in Very High Speed Framing Mode

by

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Prepared for Publication in SPIE Vol 501:

State-of-the-Art Imaging Arrays and Their Applications

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March 19, 1985

TECHNIQUES FOR OPERATING CHARGE COUPLED DEVICES (CCD's)
IN VERY HIGH SPEED FRAMING MODE

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Abstract

New concepts for operating charge coupled devices (CCD's) in a multiple frame transfer mode which allow very high speed imaging of transient phenomena are described. These methods coupled with the inherent advantages of slow scan readout, including high dynamic range, low noise and excellent linearity, provide unique, new observational capabilities.

Appropriate masking techniques allow a large portion of the CCD to be employed as a high speed image buffer. Applications include spatial imaging of rapidly moving objects, observations of transient spectral chemical phenomena and the study of rapid physiological motion.

Introduction

Frame transfer CCD's were introduced early in the development of electronic imaging as a means of providing continuous device readout at 30 frames per second. The frame transfer architecture illustrated in Figure 1 is simple in concept. In normal television operation, one-half of the CCD is defined as the image area. The other half is covered with an optically opaque mask and is defined as the storage area. The storage area is always that half of the CCD which is adjacent to the high speed serial shift register. A continuous readout is achieved by rapid parallel shifting of the integrated charge from the image area to the storage area. The stored charge is then read out serially and converted into the video signal, while a new image is integrating in the image area. If the parallel shift time is very short compared to the integration period, no shutter is required.

Full frame mode. Frame transfer CCD's were first produced with removable masks allowing the user to expose both the image and storage areas making the entire device active as a detector, hence doubling resolution. This mode dictates the use of a shutter to prevent photons from striking the device during readout.

Slow scan readout. Slow scan readout techniques are extensively used to provide substantially higher performance than can be achieved with video readout rates. The CCD is an excellent linear photometer when used in slow scan. The slow scan allows time for a solid correlated double sample, precise digitization to 14 bits or more resolution and improved charge transfer through precise clocking procedures. Since dark current is a time-dependent source of extraneous charge, slow scan modes dictate the need to cool the CCD so that negligible thermal write-up occurs during integration and readout. The slow scan mode typically employs readout rates between 10 KHz and 1 MHz.

High Speed Framing with Slow Scan Readout

Since the exposure of the CCD to light and the readout process are completely separate events, it is possible to first control the exposure and charge manipulations with high speed parallel clocking and then read the results with all of the advantages of slow scan. Figure 2 illustrates the principle of high speed framing. A small unmasked area is used to acquire the image. For example, if a 1000 X 1000 CCD array is masked so that 200 rows are left uncovered, five images of 200 X 1000 pixel resolution can be acquired in rapid succession. Obviously, some form of high speed exposure control such as stroboscopic lighting or optical gating is required to prevent image smearing.

Frame time. Given an unmasked imaging area consisting of N_i rows with a parallel row transfer frequency of f_p, the time required to transfer one image from the active image region to the storage area under the mask is

$$t_p = N_i/f_p$$

The total frame time, t_f, is equal to the sum of the parallel transfer time, t_p, and exposure time, t_e

$$t_f = t_p + t_e$$

Number of images. Since the image area is some fraction of the storage area, several images may be stored under the mask. Given the total number of rows in a CCD as N_t, the simple relationship between the vertical size of the images, N_i, and the total number of images, N_n, can be expressed as

$$N_n = N_i/N_t$$

As the vertical resolution is increased, i.e., larger frames, the frame time increases while the number of storable frames decreases. Each differing application dictates considerations of the trade-offs between resolution, frame rate and number of images required.

The parallel transfer of charge from one row to the next is limited in speed to about 1 MHz in most CCD's. The limit is caused by the long time constant introduced by the parallel gate capacitance and distributed resistance of the polysilicon gates.

Applications. Potential applications of a high speed framing slow scan readout CCD can be divided into two general classes. The first class involves the spatial imaging of moving objects or transient light sources. Possible imaging applications include the recording of combustion processes in engines, high frequency mechanical vibrations, the decay of light as a function of position in flashlamps and particle counting in rapidly flowing systems. The second general class of applications involves using the CCD in a linear mode. This involves extending the mask to cover all but one or a few rows. This linear array mode has applications in high speed spectroscopy and streak techniques. In this mode, no optical gating is required. Additionally, the parallel transfer rate need not be kept constant but can be programmed to give a nonlinear time axis. For example, in exponentially decaying phenomena, the rate can be programmed to allow high speed acquisition during early stages of observation and decreasing speed as the decay progresses. In spectroscopic operation, light is dispersed according to its wavelength along the horizontal direction as shown in Figure 3. The wavelength resolution is given by the total wavelength imaged across the row divided by the number of pixels in the row. The minimum time resolution is given by the rate at which the spectra are clocked into the masked storage area. The measurements of fluorescent and phosphorescent decay profiles, kinetic rates by stopped flow methods and bioluminescent phenomena can all be made in the wavelength region of 300 nm to 1100 nm with the time domain resolution of approximately a microsecond or longer.

Experimental

Preliminary studies have been conducted to evaluate the fast frame slow scan concept using the experimental configuration shown in Figure 4. A Photometrics, Ltd. Model 81S Camera System employing an RCA 501EX 320 X 512 element CCD was used to evaluate this technique. An adjustable mask was devised to allow accurate selection of a precise image area. A Photometrics, Ltd. Model 2021B sequential multiple stobe unit was used for all two-dimensional studies. This unit consists of six independently triggerable high intensity xenon flash lamps. A Photometrics, Ltd. Model PM8000 High Speed *Multibus-based Computer System was used for data acquisition and control. The computer system consists of a 10 MHz 68000 CPU, a 30 megabyte Winchester disk, 67 megabyte tape storage unit, 1 megabyte of random access memory and a scan converter for pictorial display. Complex camera control is provided by down-loading to the camera controller the required operational modes, including variable vertical clock rates, arbitrary size subarrays and origins, two-dimensional binning parameters and readout rates. The scan converter for user presentation and photographic recording provides 640 X 480 X 8 bit monochrome display with RS-170 compatibility.

Figure 5 shows multiple images of a Rotron Whisper fan rotating through 90 degrees of a single revolution while spinning at 1800 rpm. This study employed a frame rate of 600 frames per second with an exposure time of 50 microseconds. The mask was positioned so that five images could be obtained in rapid succession. Each image was 100 X 140 pixels.

The second study, as shown in Figure 6, capitalizes on the high aspect ratio of the 100 X 320 imaging area. The series of five images shows the falling drop formation from a liquid stream. This experiment demonstrates the precise timing that can be achieved while observing transient phenomena.

Physiological studies such as rapid eye motions, as shown in Figure 7, are easily obtained with high speed framing. The test subject was asked to move his eyes as rapidly as possible from right to left when prompted by an audible or visual cue. The strobe unit was used to provide illumination, and the frame rate was adjusted to 10 frames per second.

The experimental configuration shown in Figure 8 was employed to evaluate the very high speed linear mode operation. A phosphorescent target was excited by a 50 kilowatt, 10 nanosecond Avco Everett Laboratories nitrogen laser. The adjustable CCD mask was positioned so that only one row remained uncovered. The CCD parallel shift register was clocked at 160 KHz through 511 rows, which yields a time resolution of 6 microseconds. The laser was triggered 24 microseconds into the shifting sequence, and the phosphorescent target was focused onto the unmasked row. Figure 9 shows the intensity profile along one column of the CCD for the first 30 rows. Each point represents the integrated intensity for a 6 microsecond period. The exponential decay of the phosphor is clearly observable.

All the preceding studies benefit from the inherent advantages of slow scan digital techniques in providing instant playback, digital archival storage and 14 bit resolution. Additionally, the high quantum efficiency and low noise allow studies of transient events to be conducted at photon fluxes not suitable for more conventional techniques.

Conclusions

The combination of high speed observations of multiple images coupled with the inherent advantages of slow scan readout provide significant new capabilities for the observation of transient phenomena. The ability to vary both the frame size and frame speed allows custom tailoring of vertical resolution versus number of images. When used in a one-dimensional mode, high speed streak images may be obtained. The high speed two-dimensional mode should prove useful for studying the dynamic behavior of mechanical devices.

Acknowledgments

This research was partially supported by the Office of Naval Research. The authors wish to thank D. L. Perry for the contributions to the design and development of the multiple lamp xenon strobe bank and C. Rote for manuscript editing and preparation.

FIGURE LEGENDS

Figure 1. Frame transfer architecture demonstrating parallel transfer of information from the image array into the masked storage array.

Figure 2. The principle of high speed framing involves masking a large portion of the device to provide sufficient storage for multiple images. A small unmasked area is used to acquire images which are sequentially shifted at high rates under the mask.

Figure 3. Linear mode operation to provide high speed spectral framing is accomplished by masking all but one row of the CCD. Spectral information is then imaged on the single exposed row.

Figure 4. The experimental configuration use for spatial imaging of transient phenomena. A moving object is sequentially illuminated with a multiple lamp xenon strobe bank and displayed on a video monitor with a high resolution scan converter.

Figure 5. Multiple images of a Rotron Whisper fan rotating through 90^{o} of a single revolution while spinning at 1800 rpm. Time progresses from right to left at a frame rate of 600 frames per second and an exposure time of 50 microseconds.

Figure 6. Drop formation from a liquid stream. Time increases from right to left. The unmasked imaging area was 100 X 320.

Figure 7. Rapid eye motion taken at 10 frames per second with exposure times of 50 microseconds. Many lower speed studies benefit from the immediate replay, high photometric accuracy and digital archival storage available from this system.

Figure 8. Experimental configuration for the linear mode study. Phosphorescent decay from a target excited with nitrogen laser is observed with a CCD camera masked to expose only one row.

Figure 9. Exponential decay of laser-excited phosphorescence. Laser was triggered 24 microseconds into the shifting sequences. The time resolution is 6 microseconds per row for a total observation time of 180 microseconds.

NORMAL FRAME TRANSFER

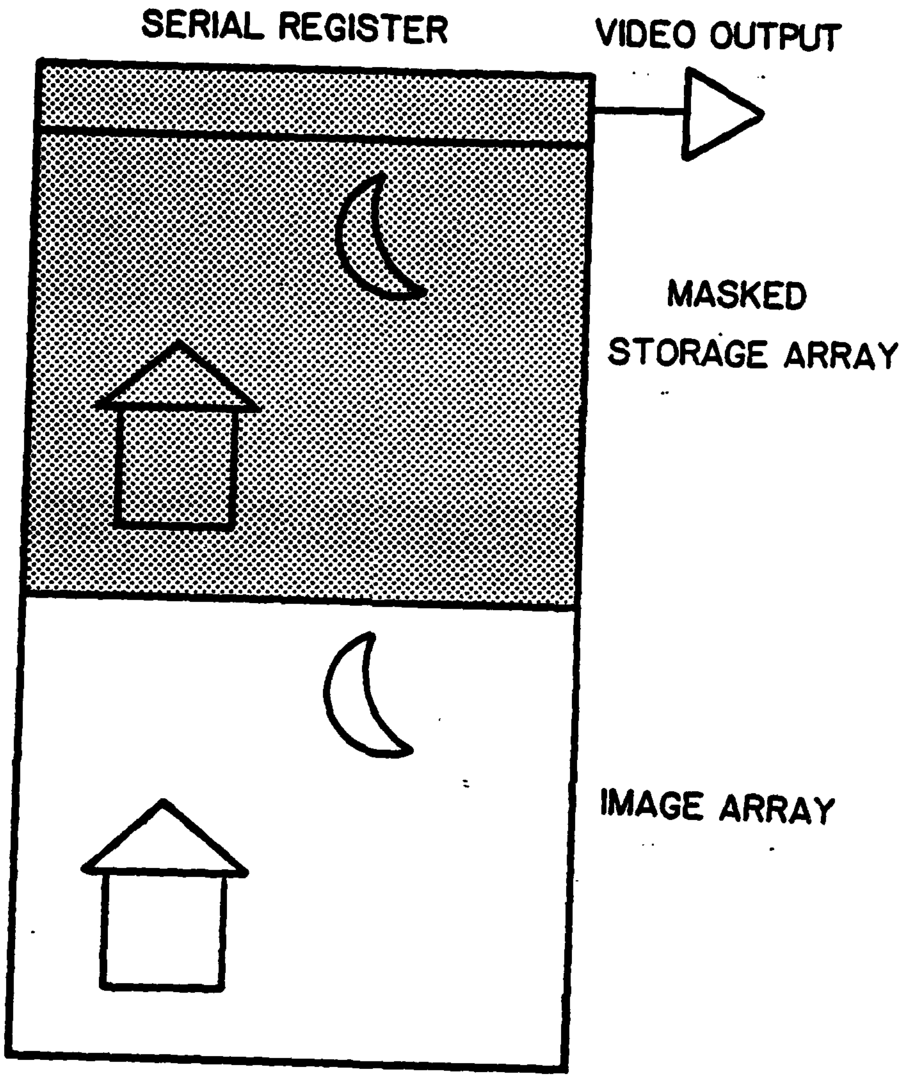


Figure 1

HIGH SPEED FRAMING

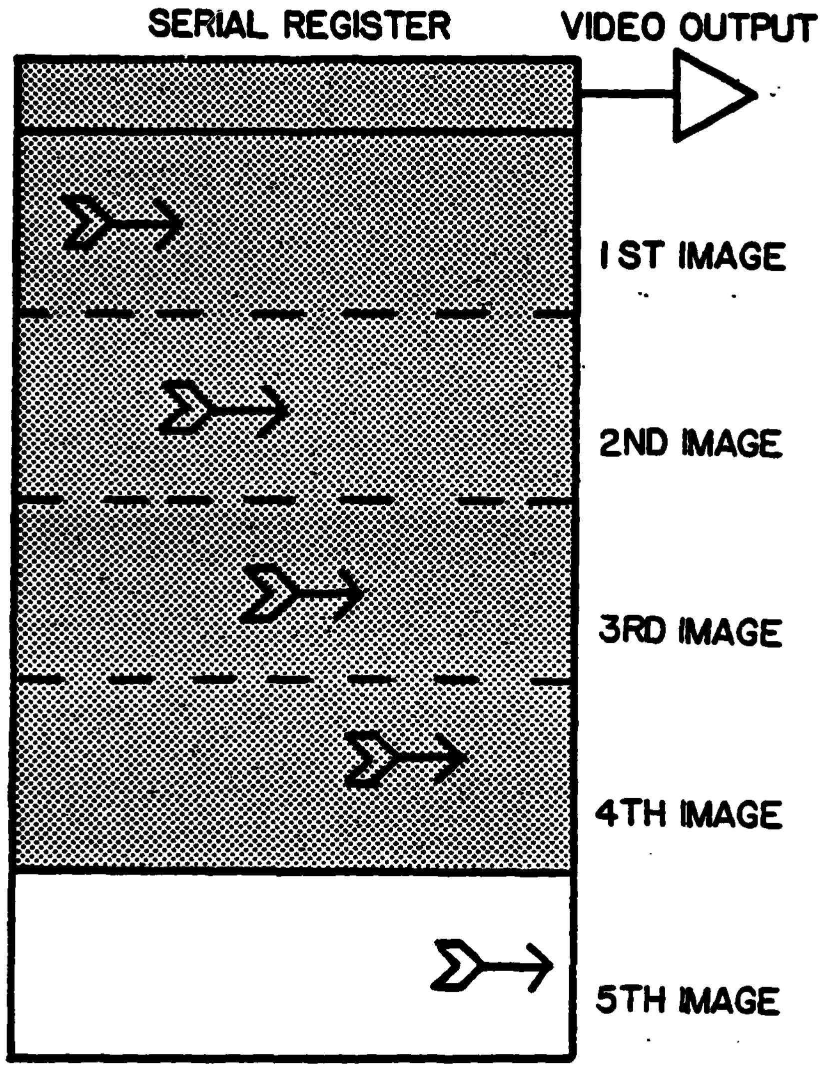


Figure 2

HIGH SPEED SPECTRAL FRAMING

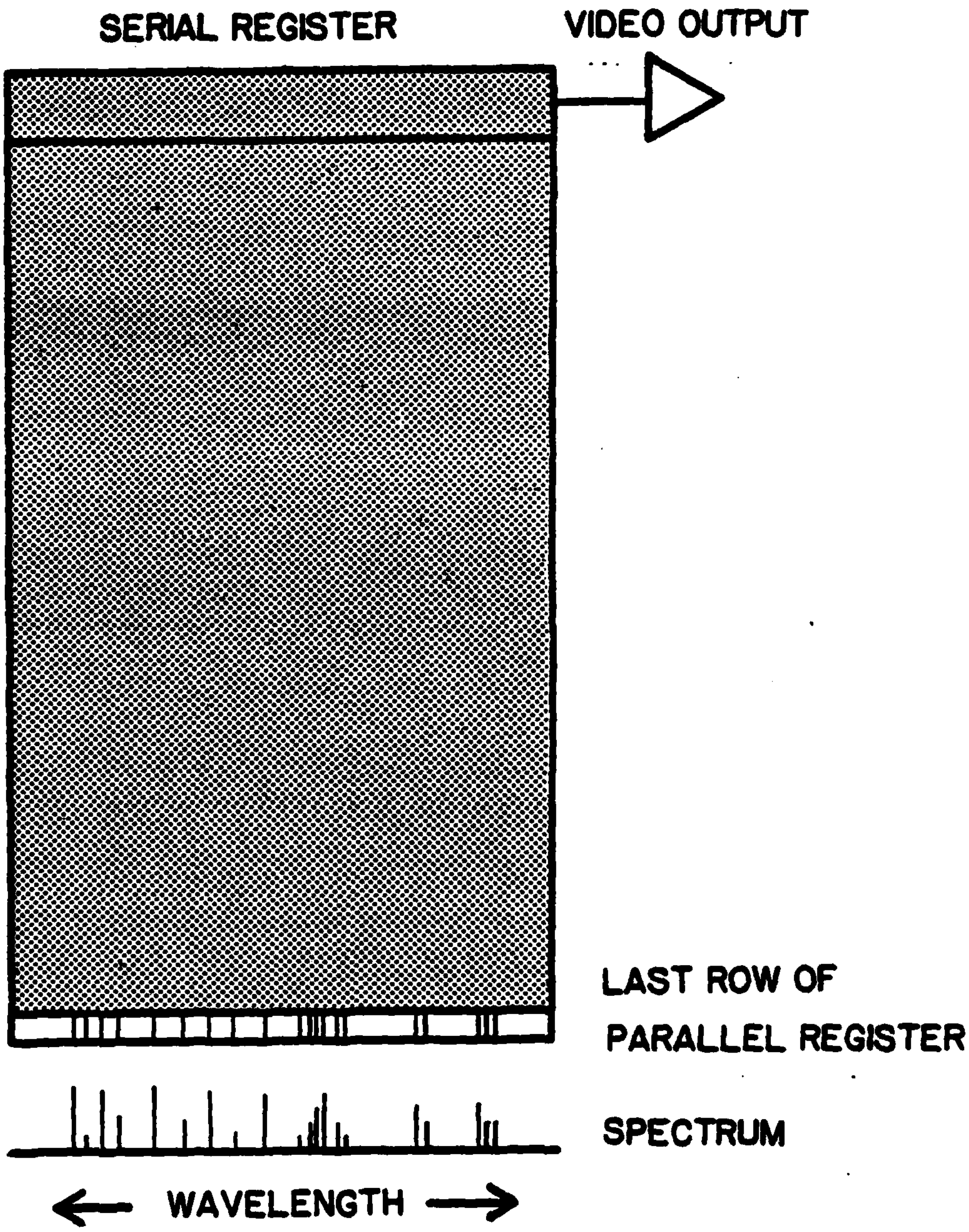


Figure 3

Figure 4

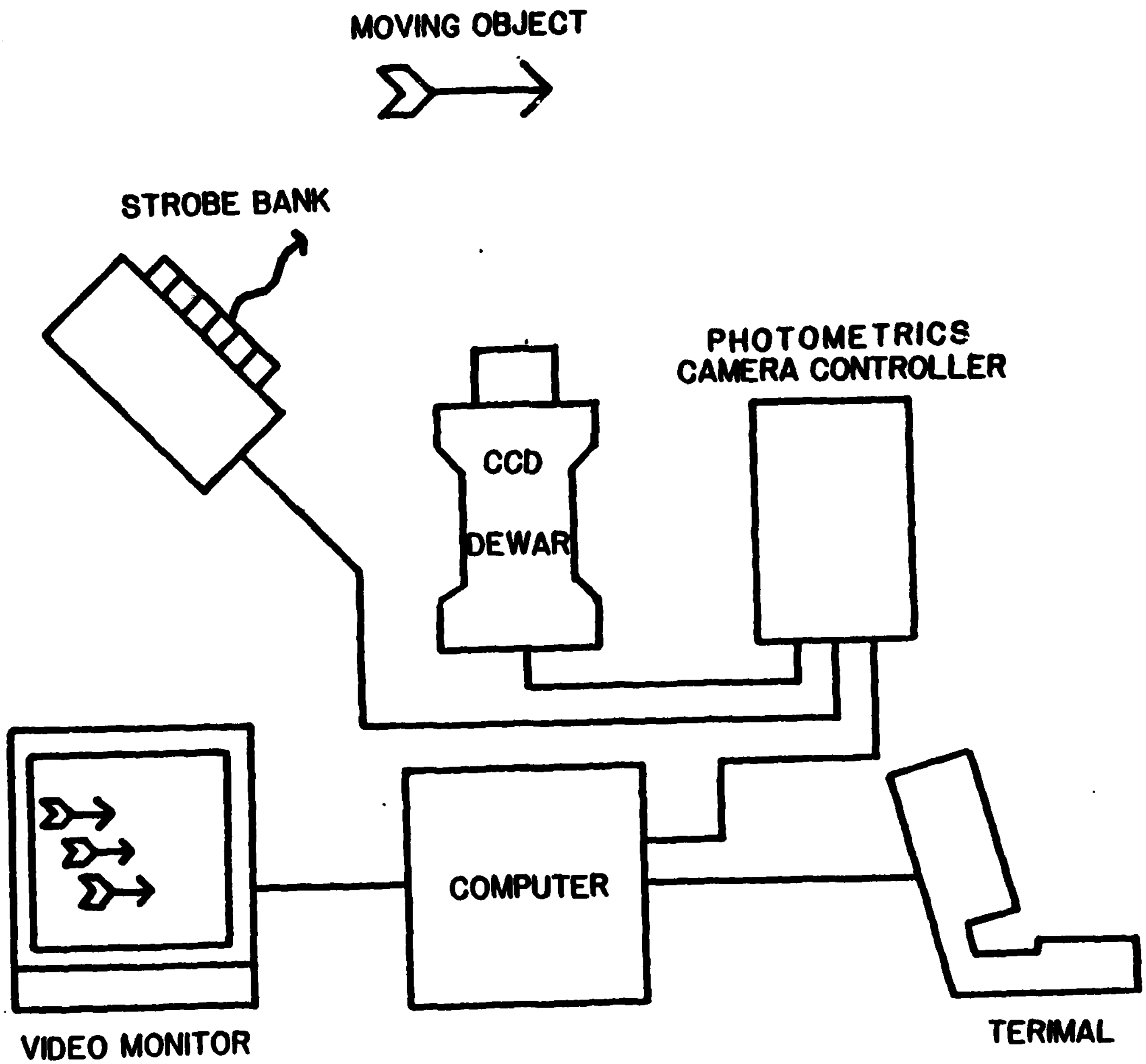
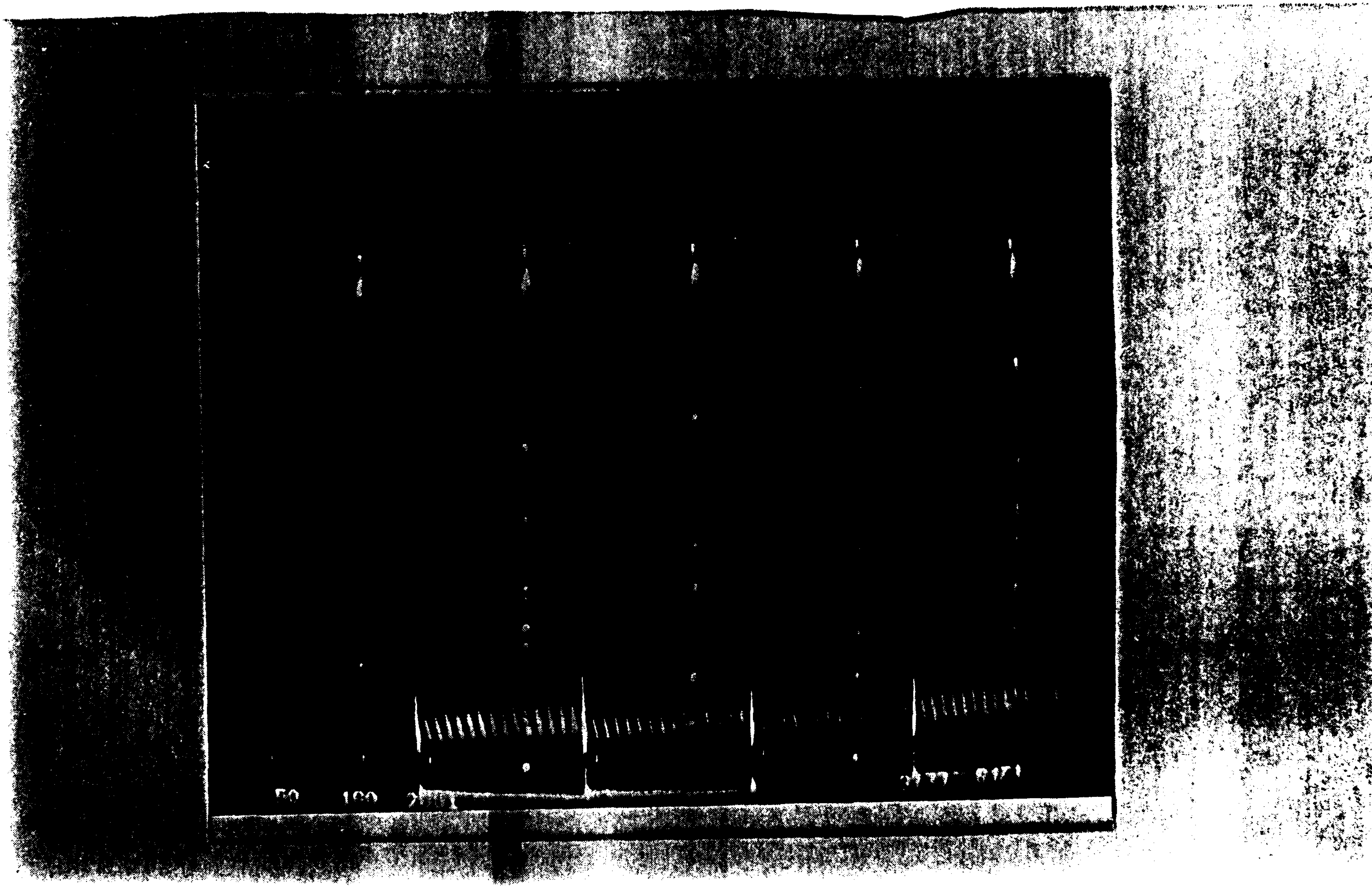

MOVING OBJECT
STROBE BANK
CCD
DEWAR
PHOTOMETRICS
CAMERA CONTROLLER
COMPUTER
VIDEO MONITOR
TERMAL

Figure 5

Figure 6



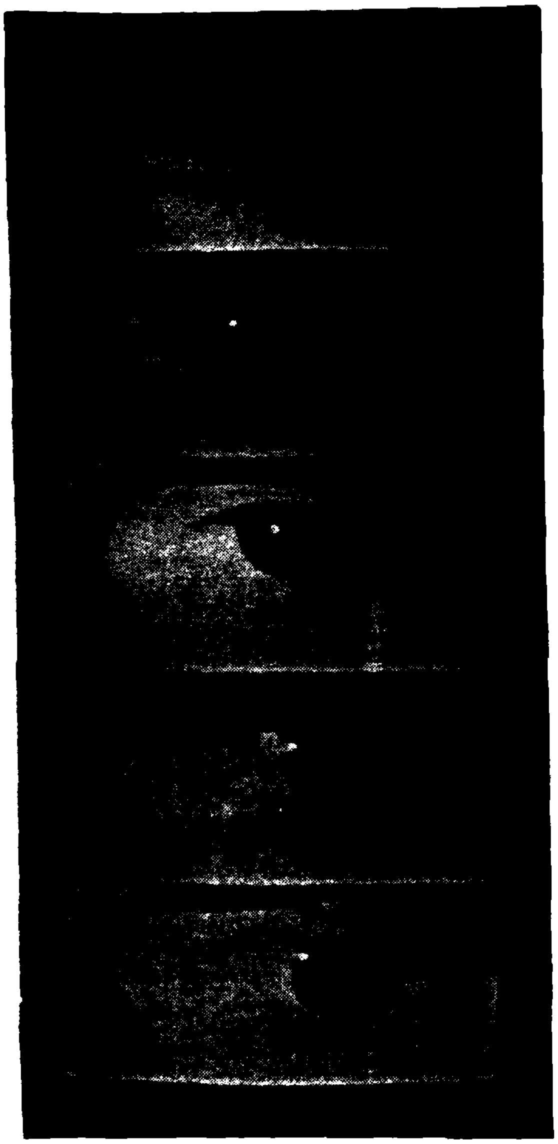
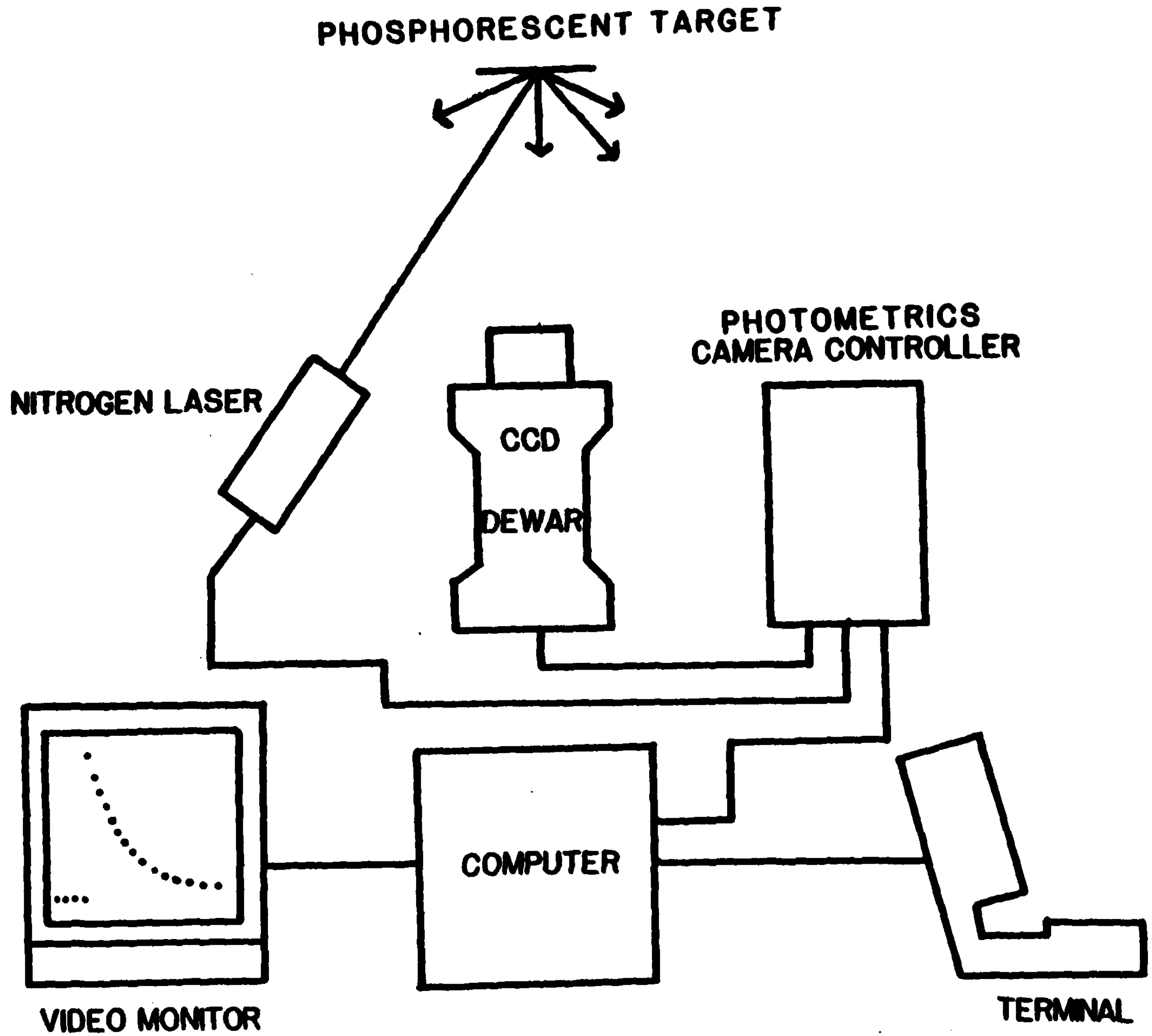


Figure 7

Figure 8



PHOSPHORESCENT TARGET
NITROGEN LASER
CCD
DEWAR
PHOTOMETRICS
CAMERA CONTROLLER
COMPUTER
VIDEO MONITOR
TERMINAL

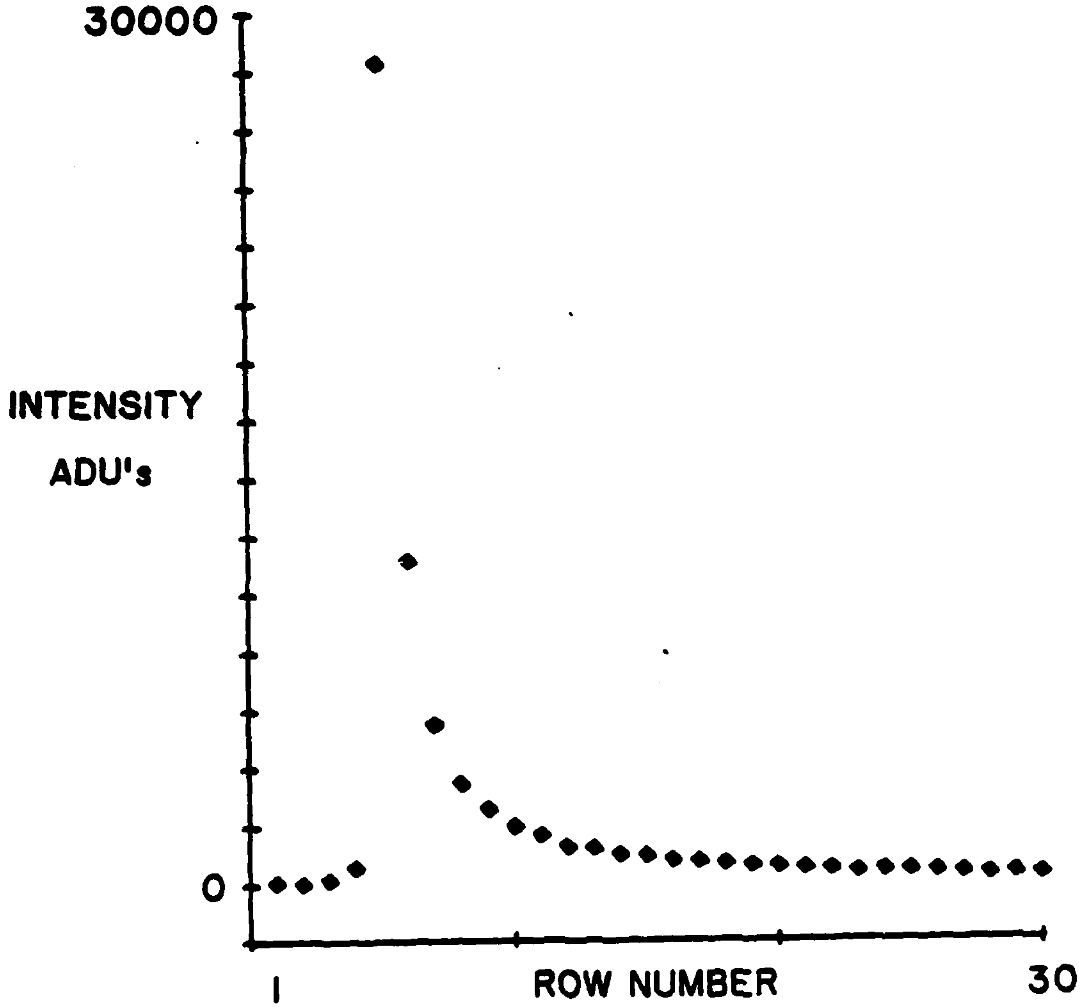


Figure 9

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